The role of plasma instabilities in the onset of detachment in the York Linear Plasma Device

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Introduction

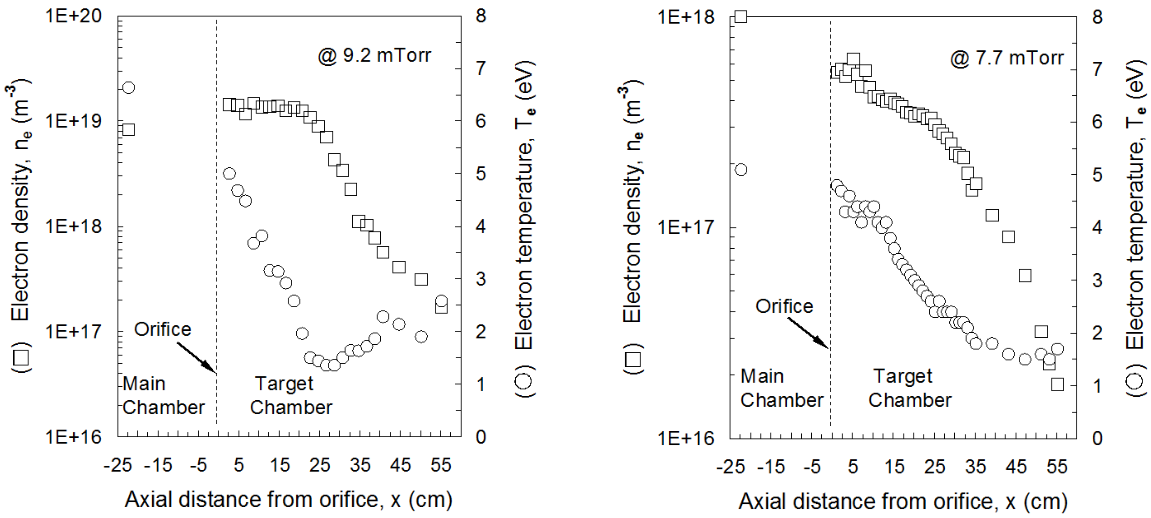
Power handling is of utmost importance in next-generation experimental tokamaks and prototype power plants, such as ITER and DEMO. The exhaust power flux to the divertor in ITER is estimated to be at least $15\,\mathrm{MW\,m^{-2}}$ [1] and could be a factor of ten higher, whereas the maximum flux for a reasonable lifetime of the tungsten divertor plates is $10\,\mathrm{MW\,m^{-2}}$ [2]. Power plant power levels are likely to be even higher, and therefore a reliable method of reducing divertor power fluxes is key to the success of fusion as a commercial energy source.

'Detachment' is already considered to be one of the more promising methods of decreasing the power loading of tokamak divertor plates. Recombination processes are induced in the plasma close to the divertor through pressure losses in the divertor region. Ion-neutral interactions (from recycling or neutral gas seeding) cool the plasma, allowing recombination reactions to take place which result in the emission of a photon [3]. This radiation is emitted into a solid angle of 4π steradians and hence reduces the amount of power incident on the divertor. The corresponding reduction in the peak ion flux is also beneficial, as it decreases the rate at which damage is done to the divertor components by sputtering due to ionic impacts. Both these effects result in extended divertor lifetimes.

Despite its promise, the physics of detachment is not yet fully understood, and experiments are being planned and carried out on experimental tokamaks such as MAST-U [4] and ASDEX Upgrade [5]. However, the toroidal geometry of the tokamak is a difficult environment in which to observe phenomena such as detachment, as diagnostic access is limited. It is therefore much more straightforward to study the divertor plasma environment in linear machines such as the York Linear Plasma Device by replicating a straightened-out field line from the tokamak scrape-off layer (SOL) and divertor region. In this way, linear machines can be used to support investigations into detachment and related phenomena. We present initial results from studies of the relationship between fluctuations and detachment on the York Linear Plasma Device.

York Linear Plasma Device

The York Linear Plasma Device (YLPD) produces a steady-state plasma of either hydrogen or helium [6]. An axial magnetic field (max. 90 mT) confines the plasma to a column with



(a) EIR (b) MAR

Figure 1: Axial density and temperature profiles for electron-ion (EIR) and molecular-activated (MAR) recombination regimes on the York Linear Plasma Device [7].

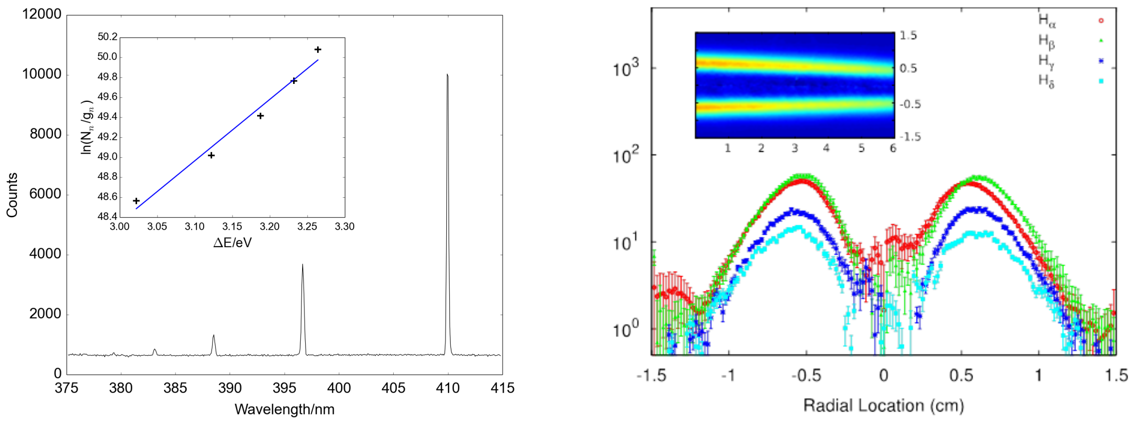
a diameter of $\sim$2 cm. The density and temperature can reach levels of around $10^{18}\,\mathrm{m}^{-3}$ and 15 eV respectively, approaching the parameters relevant to the tokamak SOL and divertor.

Two types of detachment regime have been observed previously on the YLPD: electron-ion recombination (EIR) and molecular-activated recombination (MAR) [7]. EIR processes are one-step, two- or three-body reactions, whereas MAR requires two-step interactions involving vibrationally-excited neutral molecules and intermediate charged species such as negative ions or charged molecules. Axial density and temperature profiles from this work are reproduced in Figure 1. However, the relationship between fluctuations in the plasma and the detachment process was not considered.

Observations

Initial work on the YLPD has focused on the EIR regime in hydrogen plasma, obtained by introducing neutral hydrogen gas into the target region of the chamber (away from the plasma source). EIR detached plasma is characterised by a ‘blue glow’, broader than the visible plasma column in the attached state. Optical spectroscopy (spatially- and time-averaged) of the detached region shows the high-n hydrogen Balmer emission lines responsible for the colour, as expected from consideration of the EIR processes [7]. Figure 2a shows the spectrum; the inset shows the results of a Boltzmann analysis of this spectrum. This yielded an electron temperature of $T_e = (0.16 \pm 0.06)$ eV, consistent with the low temperatures required for EIR.

Previous studies of the EIR emission in the YLPD detached plasma have yielded time-averaged radial profiles of the hydrogen Balmer emission lines (Fig. 2b) [8]. The emission predominantly originates from the ‘wings’ of the plasma column rather than the (higher density)



(a) EIR emission spectrum and Boltzmann analysis (inset). $T_e = (0.16 \pm 0.06)$ eV.

(b) Radial profile of the EIR emission across the plasma column [8]. The highest intensity occurs in the 'wings' of the column rather than in the centre.

Figure 2: Optical emission data from EIR detached plasma in the YLPD.

centre. In order to understand the causes of this observation, a high-speed Photron FASTCAM SA4 camera has been used for fast-frame imaging of the plasma. Preliminary results, taken at a frame rate of 50 kHz, show that 'blobs' or filaments of plasma are intermittently ejected from the main plasma column when in the EIR detached state. These filaments are rotating, and appear to move radially outwards. A still image is shown in Figure 3.

Ongoing work to study these filaments and their relation to detachment employs Langmuir probes to look at fluctuations in the floating potential of the plasma. Frequency analysis of floating potential time traces from the attached hydrogen plasma (Fig. 4a) shows a coherent feature at around $50-60$ kHz (dependent on the axial magnetic field), and a lower-frequency broadband spectrum (up to ~ 30 kHz). In the EIR detached regime, however, the coherent feature is absent, leaving only the broadband spectrum.

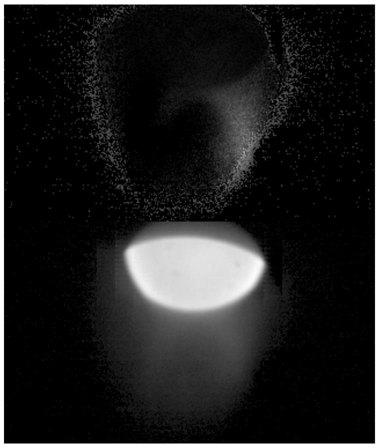
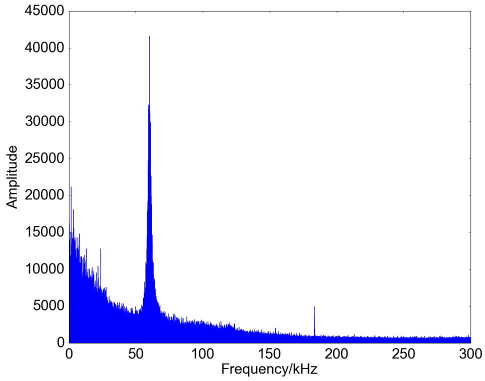
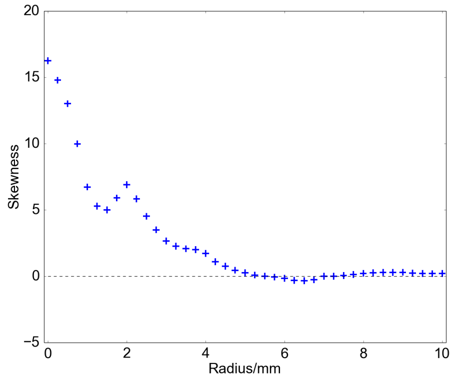


Figure 3: Still from 50 kHz imaging of the EIR-detached YLPD plasma.

The radial variation of the skewness of the low-frequency broadband section of the spectrum for the attached plasma has been analysed, and the results are plotted in Figure 4b. The skewness is positive at small and large radii, but drops below zero between ~ 5.5 and 7 mm. This appears to coincide with the positions of the phenomena observed in the detached plasma: maximum EIR emission (Fig. 2b) and the approximate position of the emitted filaments in the fast-frame imaging. The evidence obtained thus far seems to suggest a link between intermittent events and the EIR detachment process.



(a) Frequency spectrum of the floating potential signal from a Langmuir probe positioned in the centre of the attached plasma column.



(b) Radial profile of the skewness of the low-frequency broadband component of the floating potential in an attached YLPD plasma.

Figure 4: Results from spectral analysis of floating potential data for the attached YLPD plasma.

Conclusions

Preliminary observations of both attached and EIR-detached hydrogen plasmas on the York Linear Plasma Device suggest that fluctuations in the plasma may influence the process of detachment. Optical spectroscopy, fast-frame imaging and Langmuir probes are being used to study the phenomena; these diagnostics are under development to expand the range of the analyses that can be undertaken. Further work will include the use of a Thomson scattering diagnostic (to increase the accuracy of temperature and density measurements) and the extension of the study to the MAR detachment regime, using laser photodetachment to look at the negative ion species in the plasma. The results will be compared to observations that have been made in tokamaks, such as the existence of a pre-detached state on ASDEX-U in which fluctuations were seen in the soft X-ray emission. This work is essential for furthering understanding of the detachment process for implementation on ITER and future large experimental tokamaks.

Acknowledgements

Thanks are due to Nick Walkden, Richard Armitage and Kari Niemi. This work is supported by the Engineering and Physical Sciences Research Council [EP/K504178/1].

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